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Expanded color gamut reproduced by six-primary projection display

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ABSTRACT

The range of the reproducible color, i.e., color gamut, of the conventional display devices such as CRTs (cathode ray tubes) and LCDs (liquid crystal displays) is sometimes insufficient for reproducing the natural color of an object through color imaging systems. In this paper, six-primary color display is presented to reproduce the expanded color gamut, by using two conventional RGB projectors and six interference filters. The design method of the filters is also introduced to maximize the volume of the color gamut in CIE-LUV uniform color space. Using the experimental system, the gamut of the six-primary projection display is evaluated comparing with that of conventional CRTs and projectors.

Keywords: projection display, color gamut, color reproduction, primary color, real surface color

1. INTRODUCTION

Recently, with the rapidly evolving multi-media technologies and visual telecommunication systems, the color reproduction through the color imaging systems is commonly required and being currently developed. Color management technologies are actively investigated for the compensation of device-dependent characteristics of color reproduction[1]. In the color management, the standard color space, called device-independent color such as CIE-XYZ or sRGB, is defined and the color image is converted using the profile of display devices. However, the range of the reproducible color, called color gamut, is limited depending on the various display and printing device. Gamut-mapping techniques are actively studied to compensate the difference of color gamut[2], but there is a limitation that the highly saturated colors out of the gamut are impossible to reproduced by display devices.

On the other hand, in visual telecommunication apprications such as electronic commerce, telemedicine, electronic art museum, etc., the reproduction of the original color of an object, referred as a natural color, is especially important. For the natural color reproduction, the color measurement technologies are developed, for example, using the multispectral camera to achieve high accuracy in the field of medical imaging and the digital archives[3, 4]. However, the color gamut in the current display devices, such as CRTs (cathode ray tubes) and LCDs (liquid crystal displays), is limited and real surface colors are not covered[5, 6, 7]. It is difficult to reproduce the natural color of high saturation; especially paints, clothes, and so on. Thus, a display device that enables reproducing a more expanded color gamut is expected in such systems.

In order to expand the color gamut for display devices, we have proposed the multiprimary color display, using more than three primaries[8, 9]. In this work, the six-primary color projection display is developed by using the two conventional RGB projectors and six multilayer interference filters, and the capability of the reproducing expanded color gamut by six-primary display is experimentally comfirmed. The volume of the gamut in CIE-LUV color space is eveluated through the experiment, by comparing with the conventional RGB display devices. The design method of the filters is also introduced to maximize the volume of the color gamut in CIE-LUV color space. From the experimental result, the requirements for the color gamut expansion by the multiprimary display are discussed.

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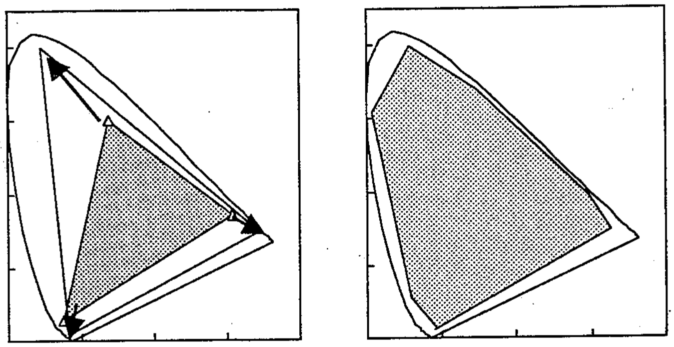

Fig.1 The concept of gamut expansion.
(a) Use "pure" primary colors.
(b) Use multiprimary (more than three) colors

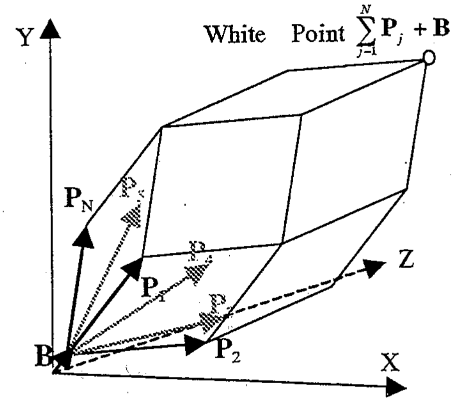

Fig.2 The color solid by multiprimary display in XYZ color space

2. GAMUT EXPANSION USING MULTIPRIMARIES

2.1 Concept of gamut expansion

In order to expand the color gamut in conventional RGB displays, the color triangle spanned by the three primaries should be enlarged by using purer primary set[10],[11], as shown in Fig.1(a). However, the gamut is still limited by triangle, it is impossible to cover the all perceptible colors by RGB display devices. On the other hand in the color printers, 4 through 7 inks are used to improve the gamut and the halftoning[12]. Applying the multiprimary approach[8],[9],[13] to the softcopy display devices has good possibility to obtain the remarkable expanded color gamut. The gamut by additive mixture of the multiprimary colors becomes a polygon as shown in Fig.1(b).

Moreover, to obtain the wide color gamut in both RGB and multiprimary display, the pure colors of narrow bandwidths are requiered for primaries. Although the attempts using the color filters attached to the front of the CRT realize to obain the pure RGB primaries[10], the loss of light is increased if the bandwidth is reduced. In the case of the projection display using the white light source, the optical light loss become large if the only three narrow bandwidth lights are used for primaries. From this point, the multiprimary display is a promising approach for the projection display to expand the gamut without the substantial loss of the light source.

2.2 Gamut by multiprimary display

To be precise, the color gamut is treated as the solid in the three-dimensional color space as shown in Fig.2, referred as the color solid. The color solid by additive mixture of multiprimaries becomes a polyhedron in CIE-XYZ color space. The model of the additive mixture of multiprimary colors is detailed as follows. When the spectral intensities of N primaries are $S_j(\lambda)$ [j=1,...,N], the total spectral intensity of the reconstructed light is given by:

$$C(\lambda)=\sum_{j=1}^{N}\alpha_j S_j(\lambda)+\beta(\lambda). \tag{1}$$

where $\alpha_j(0\le\alpha_j\le1)$ is the weight for j-th primary contributed by the modulating signal, and $\beta(\lambda)$ is the spectral intensity of the background light. Using CIE-XYZ color matching functions $\bar{x}(\lambda),\bar{y}(\lambda),\bar{z}(\lambda)$, the color in CIE-XYZ color coordinates $\mathbf{c}=[C_x,C_y,C_z]^t$ reconstructed by additive mixture of N primaries are given by:

$$\mathbf{c}=\begin{pmatrix}C_x\\C_y\\C_z\end{pmatrix}=\sum_{j=1}^{N}\alpha_j\begin{pmatrix}\int\{S_j(\lambda)+\beta(\lambda)\}\bar{x}(\lambda)d\lambda\\\int\{S_j(\lambda)+\beta(\lambda)\}\bar{y}(\lambda)d\lambda\\\int\{S_j(\lambda)+\beta(\lambda)\}\bar{z}(\lambda)d\lambda\end{pmatrix}=\sum_{j=1}^{N}\alpha_j\mathbf{P}_j+\mathbf{B} \tag{2}$$

where $\mathbf{B}$ is the color coordinates of the background light and $\mathbf{P}_j$ is the color coordinates of j-th primary color in disregard of the background light, respectively. $\mathbf{P}_j$ and $\mathbf{B}$ are outlined in Fig.2. The region of $\mathbf{c}$ represented by eq.(2)

with the constraint of $0 \le \alpha_j \le 1$ is the gamut , i.e. the color solid, by additive mixture of N-primaries in CIE-XYZ color space. By applying adequate weight α_j to each primary color, arbitrary color inside the color solid can be reproduced as shown in eq.(2). The method to compute the signal corresponding to α_j is discussed in section 2.4.

If the contrast ratio of the display system is not high enough, the background light is mingled with the reconstructed color, then the color saturation becomes reduced. As shown in Fig.2, the color solid is shifted up in its entirety due to the color coordinate of the background light **B**; especially the color gamut in dark region is shrunk. In order to suppress the background light, the improvement of the contrast of display devices is very important for the display of wide color gamut[11].

2.3 Volume of the gamut

In order to evaluate the gamut size of the display system, the volume of the color solid in CIE 1976 LUV uniform color space is preferable[10]. Let us now formulize the volume of the gamut by multiprimary display in CIE-LUV uniform color space as follows; Since the color solid of the multiprimary display in CIE-XYZ color space is represented by eq.(2) with the constraint of $0 \le \alpha_j \le 1$, the set of the reproducible colors by multiprimaries in the CIE-LUV uniform space is given by:

$$G = \left\{ \Re(\mathbf{c}) \middle| \mathbf{c} = \sum_{j=1}^{N} \alpha_j \mathbf{P}_j + \mathbf{B}, 0 \le \forall \alpha_j \le 1 \right\}, \tag{3}$$

where $\Re$ is the operator transforming the CIE-XYZ color space to the CIE-LUV color space $\Re : [X, Y, Z] \Rightarrow [L^*, u^*, v^*]$, and $[L^*, u^*, v^*]$ is the color coordinates in CIE-LUV uniform color space defined by:

$$\begin{cases} L^* = 116(Y/Y_0)^{1/3} - 16 \\ u^* = 13L^*(u' - u'_0) \quad , u' = 4X/(X + 15Y + 3Z) \\ v^* = 13L^*(v' - v'_0) \quad , v' = 9Y/(X + 15Y + 3Z) \end{cases}.$$

where Y_0, and (u'_0, v'_0) are the luminous and the CIE-UCS chromaticity coordinates of the reference white under the observer illumination, respectively. Then, the volume of the gamut by multiprimary display is determined by:

$$V = \oint_G dL^* du^* dv^* \tag{4}$$

The section of the color solid in (u^*, v^*) plane at each L^* is represented by the polygon, so that the three-dimensional integration of eq.(4) could be calculated by integrating the area of that section in the direction of L^*. Note that the volume can be defined only if the luminous of the observer illumination is determined.

Moreover, in order to display the natural color of real-world objects, the color solid should cover the all exsisting colors as possible. Pointer has published data defining the maximun gamut of the existing surface colors, called Pointer gamut[5], in uniform color space. Therefore, as a reference for the gamut evaluation, the ratio of the reproducible color within the Pointer gamut in CIE-LUV space is given by:

$$W(\%) = \frac{100 \times volume(G \cap G_p)}{volume(G_p)}. \tag{5}$$

where G_p is the finite set of the colors limited by the Pointer gamut in CIE-LUV color space. In this paper, this reference is also involved in the design of the filters used to construct the six-primary projector.

2.4 Color conversion

To display the natural color, the image represented by the color coordinates, such as CIE 1931 XYZ coordinates are required. Once the coordinates in three-dimensional color-space is given, we have to compute the signal corresponding to the weight for each primary color α_j [j=1,...,N] given in eq.(2). The signal for each primary can be calculated by the inversion of eq.(2), considering the dynamic range of the display device, i.e., the inversion of eq.(2) should be kept under the restraint as $0 \le \alpha_j \le 1$. Also it should be note that the conversion to N-dimensional signal space from three-dimensional color space involves a degree of freedom due to the metamerism.

One of the solution to realize the conversion considering the constraint is to use the look-up-table (LUT), however, the LUT size is very large, i.e. three dimensional LUT in the color space are required.

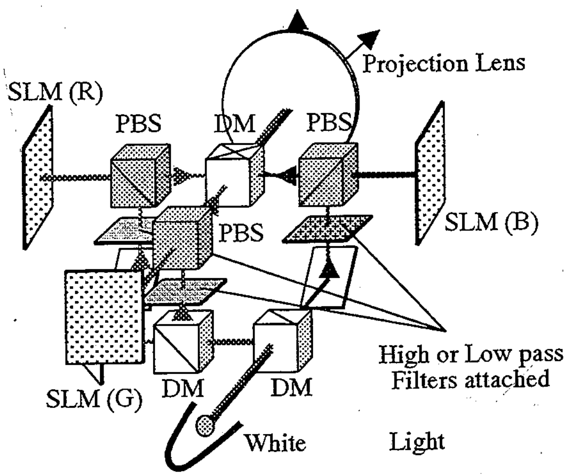

Fig.3 The optical configuration for the six-primary projectior (one of two projectors). Filter is attached on the optical path of R,G,B light splitted by the dichroic mirror (DM). PBS is the polarized beam splitter for SLM.

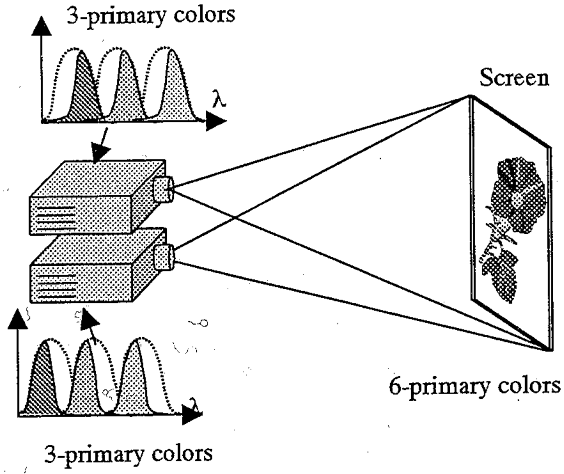

Fig.4 The setup for the six-primary projection display. The images of two projectors is superposed on the screen.

As alternative method, dividing the polyhedral color solid into sub-tetorahedrons, the signal for the all color inside each sub-tetorahedrons are calculated by liner interpolation using the signals at the corner point of the correaponding tetorahedrons. This conversion is simple to compute the signal with the constraint; it needs some matrices for liner transforms, equal to number of tetrahedrons, after the computation to judge whether the color is included in each tetrahedron.

3. SIX-PRIMARY PROJECTION DISPLAY

3.1 Constraction of the projection system

In this section, the experimental system of the six-primary projection display constructed using two conventional LCD projectors is introduced. In this system, two projectors (Victor, D-ILA projectors), which have three reflection-type liquid crystal panels, are used. In each projector, the light emitted from the white light source is separated into R, G, and B lights by dichroic mirrors, as shown in Fig.3. To obtain the primary lights of narrow bandwidth, the six multilayer interference filters are attached (see Fig.3) on the optical path of R,G, and B lights of the two projectors; Three high-pass filters are attached on the one projector and the three low-pass filters are attached on the other. The six monochromatic images contained at different wavelength from two projectors are superposed on the screen as shown in Fig.4, so that the color image is reconstructed on the screen by additive mixture of six primaries.

To align the image projected by the two projectors, the trapezoidal distortion due to the disparity between the two projectors should be compensated. For this purpose, the mesh images projected by each projector are captured by CCD camera to find the parameter of the distortion, and the image for each projector is pre-distorted to compensate it. Assuming that the abberation of the projection lens is not appeared on the projected image, the relationship between the coordinates of the original image (x_o, y_o) and the projected image on the screen (x_p, y_p) is represented as the perspective projection given by;

$$\begin{cases} x_p = (cx_o + dy_o + e)/(ax_o + by_o + 1) \\ y_p = (fx_o + gy_o + h)/(ax_o + by_o + 1) \end{cases}, \tag{6}$$

where a, b, c, d, e, f, g, h are referred as the parameters of the distortion. These parameters are estimated in each projector by the projected image captured by CCD camera. The image for each projector is pre-distorted by the

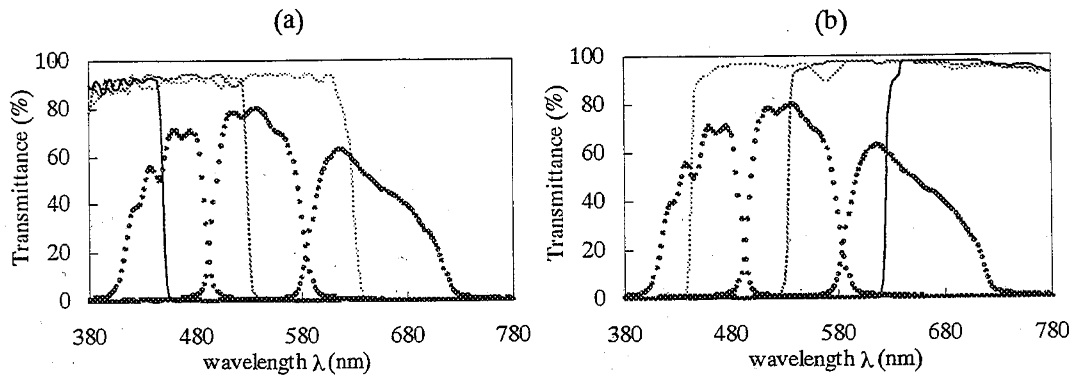

Fig.5 The spectral transmittamce of the (a) low-pass and (b) high-pass filters.
The relative spectral intensities of the RGB lights also shown (dotted line).

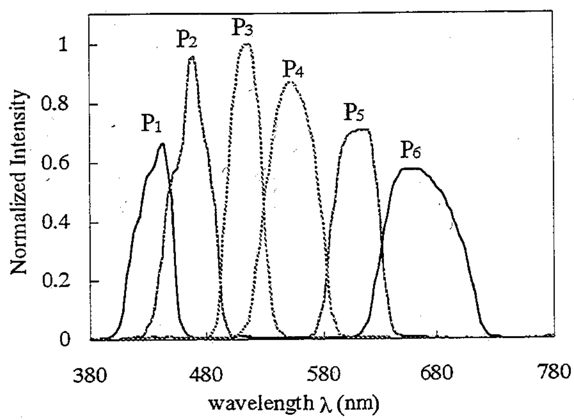

Fig.6 The spectral intensities of six primary colors (P_1~P_6).

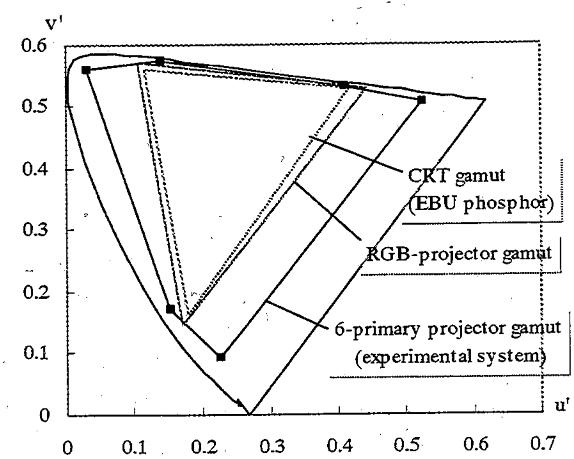

Fig.7 The color gamut reproduced by the experimental system (solid line). The color gamut of the conventional EBU phosphor (gray triangle) and the RGB projector (solid triangle) is also shown.

inversion of eq.(6), then the distortion of the each projected image is compensated and the images from two projectors are superposed on the screen. Strictly speaking, the disortion of the cupturing image due to the abberation of CCD camera lens, if appeared, should be cariblated in advance.

3.2 Filter design

To obtain the enhanced color gamut of the projection system, the filter set used in this projector is designed to maximize the volume of the gamut in CIE-LUV uniform color space. The high and low pass filter is used in this projection system, the optimal cut-off wavelength is determined in this filter design as follows. When the cut-off wavelengths of the high and low pass filter set are given as λ^L_k and λ^H_k [k=1,2,3], we assume the approximate spectral transmittance of the low and high pass filters, $f^L_k(\lambda)$ and $f^H_k(\lambda)$, as:

$$f^H_k(\lambda)=\begin{cases} T_{max} & ,\lambda>\lambda^H_k \\ T_{min} & ,\lambda<\lambda^H_k-\Delta \\ (\lambda-\lambda^H_k)\beta+T_{min} & ,\lambda^H_k-\Delta\le\lambda\le\lambda^H_k \end{cases} \text{, and } f^L_k(\lambda)=\begin{cases} T_{max} & ,\lambda<\lambda^L_k \\ T_{min} & ,\lambda>\lambda^L_k+\Delta \\ (\lambda^L_k-\lambda)\beta+T_{min} & ,\lambda^L_k\le\lambda\le\lambda^L_k+\Delta \end{cases} \quad (8)$$

where $\beta = (T_{max} - T_{min}) / \Delta$, T_{min} and T_{max} are transmittance of transmit region and reject resion, about 90 (%) and 0.1 (%), respectively, and Δ is the bandwidth of transition region from transmit and reject region, about 10 (nm). Using these filters to modulate the RGB lights of two projectors, the spectral intensity of each primary color is given by:

$$S_{2k}(\lambda) = t_k(\lambda) f^L{}_k(\lambda)$$
$$S_{2k+3}(\lambda) = t_k(\lambda) f^H{}_k(\lambda) \qquad (9)$$

where $t_k(\lambda)$ are the spectral intensity of R, G, and B light of the projector without filtering, respectively. The volume of the color gamut in CIE-LUV space and the ratio of the reproducible color within the Pointer gamut are calucurated by using eq (2) though (5), if the background light of the projection system and the observer illumination is determined. In this design, the coordinates of the backgound light **B** is determined by $\mathbf{B} = 1/r_c \sum_{j-1}^{6} \mathbf{P}_j$, where r_c is the contrast ratio (white/black ratio measured by spectrophotometer, about 140 in this system). The observer illumination is assumed that the chromaticity is CIE standard illuminant C (u_0, v_0)=(0.2009, 0.4609), and the luminous is equal to that of the white point of the projection system to compensate the difference of the total luminous according to the difference of the cut-off wavelength.

As the result of calculating this process in all the combinations of six cut-off wavelengths varied from 380 (nm) to 780 (nm) at intervals 10 (nm), the optimum cut-off wavelengths to maximize the ratio of eq.(5) is determined; The cut-off wavelengths of high-pass filter attached on the optical pass of R, G, and B light of one projector are 620, 540 and 440(nm), respectively, and that of low-pass filters on the other projector are 620, 540 and 450(nm). The spectral trancemittance of these six inteference filters are shown in Fig.6. As a result, the spectral intensities of the primary lights shown in Fig.7 are obtained. In Fig.7, P_1 and P_2 are generated from blue light, P_3 and P_4, P_5 and P_6 are from green and red lights, respectively.

4. EXPERIMENTAL RESULT

In the experiment, the color gamut reproduced by the six-primary projection display is evaluated by measuring the each primary color and the background light of the experimental system. All the measurements shown below are obtained by rear-projection display. The color patchs of the primary colors and the black is projected by the experimental system on the screen, the coordinates of these color patches is measured by spectrophotometer in the dark room. The color coordinates of each primary obtained by this system is indicated in Fig.8. Expanded color gamut is obtained as compared with the conventional CRT and the RGB projector, especially in purple, green and red region.

Table.1 shows the volume of the gamut in CIE-LUV color space calculated by eq.(4), which is comparing the six-primary projector with the RGB projector (original D-ILA projector) and the CRT television monitor (ikegami, TM20-17R). Since the brightness of these display devices is defferent each other, the volumes of the gamut are compared in this table under the two conditions as follows:

V_a is the volume of the color solid on the absolute scale assuming the absolute luminous of each display device.
V_r is the relative volume of the color solid normalized as the maximum luminous of the white point Y_w[cd/m^{2}sr] of each display device, i.e., the volume of the color solid represented by (Y_0/Y_w)c shown in eq.(3).

	Y_w [cd/m^2]	V_a ($\times 10^6$)	V_r ($\times 10^6$)
Experimental system *	371	1.31	1.91
RGB Projector *	436	1.04	1.23
CRT monitor	225	0.56	1.52

Table.1 Comparison of the absolute volume (V_a) and the relative volume (V_r) of the gamut in CIE-LUV color space. Y_w is the luminous of white point of each display device.

* when the projection distance is about 2 [m] and the image size is 50 [inch] diagonally.

	W_a [%]	W_r [%]
Experimental system *	81.8	99.6
RGB Projector *	69.7	84.3
CRT monitor	40.7	85.8

Table.2 Comparison of the ratio of the reproducible color within the Pointer gamut. W_a means the percentage when the luminous of observer illumination is Y_0=500. W_r means the percentage when the luminous of observer illumination is equal to Y_w of each display device.

In this table, observer illumination is assumed to be CIE standard illuminant C, and the white balance is adjusted to the illuminant in each display device. The luminous of the illumination is assumed by Y_0=500 [cd/m^{2}sr] corresponding to the illumination for well lighted indoors about 1500 [lx].

From this result, the remarkable expanded color gamut is obtained by the six-primary projection display compared with these conventional RGB display devices. In the evaluation of the relative volume V_r, the volume of the gamut is enlarged by the six-primary projection display in spite that the volume of the projection display is smaller than that of CRT monitor due to insufficiency of the contrast. Furthermore, although the luminous of the six-primary display is slightly smaller than that of the original RGB projector, referred as Y_w shown in the table, the expanded color gamut is obtained by six-primary projection display.

Table.2 shows the ratio of the reproducible color within the Pointer gamut, obtained by eq.(5), under the same conditions mentioned above. Although the absolute luminous of the experimental system is still insufficient to reproduce the all real surface colors under the bright illumination, nearly all the Pointer gamut (99.6%) is covered by the gamut of the six-primary display if the luminous of the illumination is adjusted.

To show the color reproduction ability of the six-primary display system, the colors of 24 samples are measured by a spectrophotometer and displayed. The color coordinates are converted by calculating the inversion of eq.(2), such that the signals are within the dynamic range of the SLM. The results are presented in Fig.8, both the colors within and out of the color gamut of the conventional RGB display device are successfully reproduced.

Fig.9 is the photograph of the color image, the wooden palette painted by the oil and acrylic colors, displayed by the experimental system. The color image of the object, represented by CIE-XYZ values, are estimated by capturing the 16-band images taken by a multispectral camera, and is converted to the signals for six-primary by above mentiond. In Fig.9, the distortion of the projectors is successfully compensated and the high-resolution six-primary color image could be obtained. Although the photograph could not show the ability of color reproduction, we comfirmed visually that the colors of the paints, including the highly saturated color out of the CRT gamut, are almost perfectly reproduced by the six-primary color projection display.

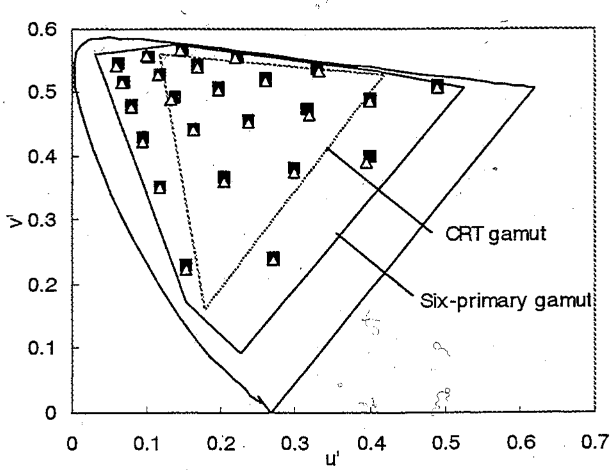

Fig.8 Coordinates of reproduced colors by six-primary display (white symbols), of 24 samples that have the colors shown by black symbols.

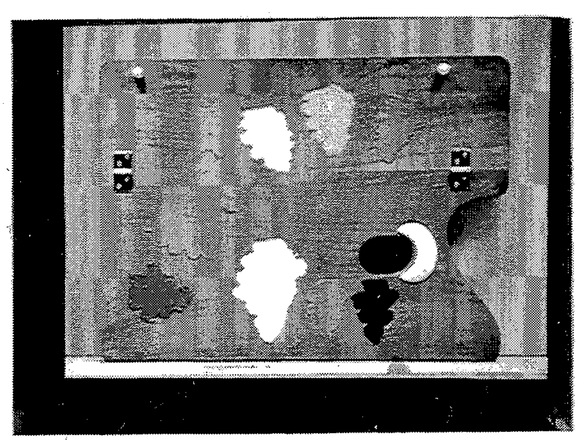

Fig.9 The black and white photograph of the color image reproduced by the six-primary color display

5. DISCUSSION AND CONCLUSIONS

In this paper, the six-primary projection display using the two conventional RGB projectors is presented and the experimental results are illustrated. Through the experiment, the volume of the color gamut in CIE-LUV uniform color space is evaluated, the remarkable expanded color gamut is obtained by the system compared with the

conventional RGB display devices. Especially, it is confirmed that 99.6 (%) of the Pointer gamut is covered by the gamut of the six-primary display if the luminous of the illumination is adjusted.

The experimental system using the two conventional projectors is very simple to construct and the six-primary image with high-resolution and wide color gamut could be obtained easily, although the optical efficiency is not so high because of the absorption of the filters, i.e., almost half of the RGB light is absorbed to generate each primary of narrow bandwidth.

To obtain enough the effect of the gamut expansion by multiprimary projection display, the optical loss of the light source shoud be small as possible. In order to reproduce the natural color under the brightened illumination, the optical efficiency of the display system shoud be improved making effective use of the spectrum of the light source by using DOEs, HOEs[8], [14], [15], and dichroic mirrors.

If the background light is mingled with the reconstructed color, the color saturation becomes reduced. Therefore, it is essencial to improve the contrast of the display device, such as the improvement of the SLM, elimination of the flare, and so on.

The digital micromirror device (DMDs)[16] has good possiblility for the multiprimary projection display to obtained the wider color gamut, with the high contrast and the high brightness.

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